Determination of drainage resistance coefficients under known shear rate

MARK A. PARADIS, JOSEPH M GENCO, DOUGLAS W. BOUSFIELD, JOHN C. HASSLER, AND VAUGHN WILDFONG

ABSTRACT: The drainage rate of papermaking stock determines the design and operation of the wet end of a paper machine. For single and twin wire machines with various elements, the effectiveness of the draining process cannot be quantified unless there are good numbers for the drainage resistance of a given pulp under conditions that resemble the industrial process. A recently developed laboratory drainage device can estimate the viscous drainage resistance at short times and high drainage rates. However, this device has no shear on the pulp during drainage. This paper presents a new method to measure the drainage rate under known shear conditions. We report the influence of shear rate and various constituents in lightweight coated (LWC) paper on drainage rate. We also investigated the effect of shear rate on drainage resistance.

Application: Design of paper machine formers, drainage rates on existing paper machines, headbox slurry characterization.

Pulp drainage rates and viscous resistance coefficients are a function of the physical properties of the paper furnish. Important factors influencing wet end drainage are pulp composition, average fiber length, fiber length distribution, fines content, charge level on the stock, and degree of stock hydration. Stock drainage also depends on the chemical processing aids such as starch, coagulants, flocculants, and wet-strength additives and the level of shear present on the wet end of the paper machine. Drainage rates have been difficult to quantify at industrial significant conditions.

Standard methods to characterize drainage rates, such as the Canadian Standard Freeness (CSF), are good for quality control and comparison with other stock, but these tests do not provide usable fundamental parameters for models that predict pressure distributions and drainage rates during forming. Models for pressure distribution, as described by Zhao and Kerekes [1], Zahrai and Bark [2], Roshanzamir *et al.* [3], Green [4], Green *et al.* [5], and Dalpke *et al.* [6], all depend on some parameter—often called drainage resistance coefficient or a Darcy law coefficient—that relates the dewatering rate with the pressure. In theory, this parameter should be a standard measurement of pressure drop across a mat of pulp. In fact, this coefficient depends on basis weight and other local conditions and is difficult to measure for conditions that mimic the high speed and short-time drainage conditions of a modern paper machine. Mantar *et al.* [7] reported some short time drainage results, but the time scale and conditions were long compared to that of an actual paper machine. The reported drainage resistance was not constant; it increased as the mat thickness increased. This result pointed to the need for a short time and thin mat test.

Wildfong *et al.* [8, 9] described a rapid drainage tester and showed that the results can help predict pilot scale data. The test used a laser triangulation sensor to measure the motion of the liquid free surface during drainage. The test was rapid with drainage rates that matched industrial conditions. The resistance coefficient again increased as the mat formed, although in filtration theory, this coefficient should be constant. The drainage resistance should increase with the mat thickness, but the specific cake resistance should be essentially constant except when there is a very large increase in pressure drop across the mat, which would not be expected on the wet end of a paper machine.

Fines retention plays an important role in the change in resistance coefficient with time. Certain grades, such as newsprint, show a rapid increase in the coefficient while others show a moderate increase. Other tests suggest that the increase in the resistance coefficient is a result of fine material being trapped in different layers of the forming mat, causing that mat to have different viscous resistance values in the different layers. In spite of the changing resistance coefficient, we should be able to use the average values in the models above to obtain good predictions or build a dependence on mat thickness into the models.

The largest short-coming of the method described by Wildfong *et al.* [8] is that the pulp suspension is not exposed to shear during drainage. Hung *et al.* [10] describe a donut-shaped piston cylinder apparatus under development for determining the permeability of pulp fiber under simulated forming conditions. A transducer in the piston will serve to measure the flow rate through piston displacement and pressure. Shear is applied by rotating the wire on the inside surface of the device. This device has the potential to characterize short time rapid dewatering under shear, but we have not seen reports of results so far.

Arslan *et al.* [11] investigated a method to measure retention at a known shear rate. They used an inverted cone to generate a known and uniform shear rate in the region over the wire in an apparatus that resembles a cone-and-plate rheometer. The drainage region is measured at a known and uniform shear rate during a retention test. They compare results to the standard Britt jar and report them for different systems. Arslan *et al.* also report some drainage rate data [11] measured over long time periods that do not match industrial drainage rates.

In this work, we describe a new drainage apparatus that permits accurate estimation of the drainage resistance of headbox and other papermaking stock samples under industrially significant conditions. The new apparatus builds upon the previous work of Wildfong *et al.* [8] and Arslan *et al.* [11]. The drainage rate is determined by a conductance measurement in the stock remaining in the shear cell. We report results for a number of pulp suspensions and for different shear rates.

EXPERIMENTAL

The theory and basic experimental apparatus are described by Wildfong and coworkers [8], while the shear cell is described by Arslan [11]. Darcy's law can be modified to define the drainage resistance (a) of a paper stock as it is being filtered on the wet end of a paper machine.

$$\frac{\Delta P_m}{L} = av \tag{1}$$

In the above equation (ΔP_m) is the pressure drop across the fibrous mat that is building. We have defined the thickness of the mat to be (L) when the superficial drainage velocity is (v). To estimate the drainage resistance (a), we must construct an apparatus that simultaneously measures the pressure drop (ΔP_m), the mat thickness (L), and drainage velocity (v) in real time.

Drainage apparatus

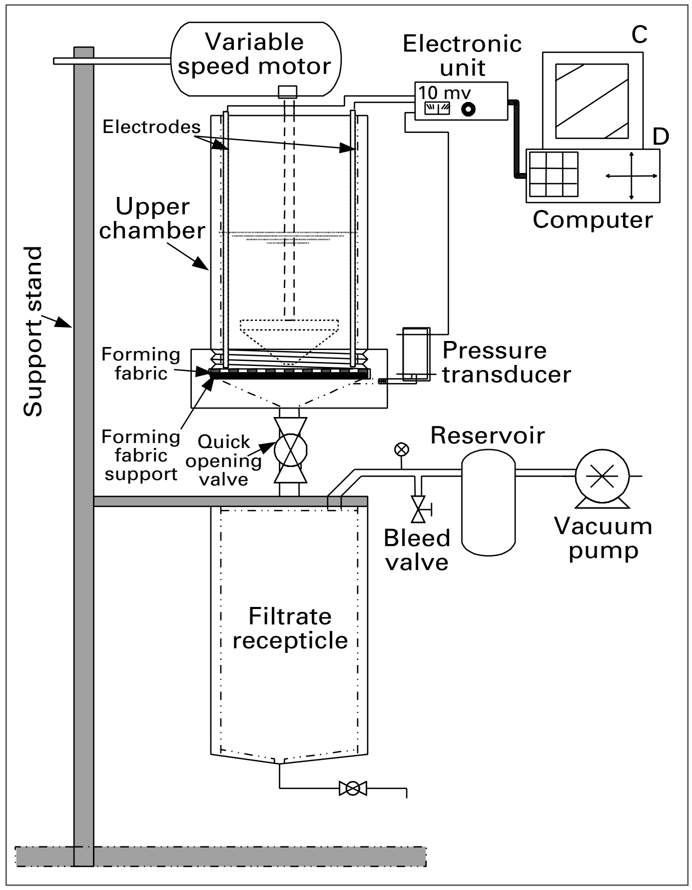
The drainage apparatus (**Fig. 1**) consists of an upper chamber equipped with a forming fabric, fabric support, and pressure transducer located under the forming fabric. The pressure transducer gauges the differential pressure across the mat and the forming fabric. A pair of electrodes estimates the volume of the slurry remaining in the shear cell in real time. The differential pressure across the mat and forming fabric is induced by a vacuum pump, which is connected to the filtrate receptacle using a large reservoir that functions as a capacitance in the system. A quick opening value separates the upper chamber and the filtrate receptacle. In the experiment a known vacuum is drawn on the stock, which is allowed to drain very rapidly through the forming fabric.

The upper chamber uses a cone-and-plate rheometer to apply a quantifiable shear field to fluid as it passes through the thickened mat and the filtration media. Therefore, the drainage takes place under a known and uniform shear rate. The signals from the electrodes and the pressure transducer are recorded by a computer in real time. The data collection frequency is 500 Hz. We use the data to estimate the drainage velocity (v). Drained liquid is analyzed to determine the overall retention coefficient (R), while the material remaining in the drainage apparatus can be tested for water retention value (WRV), composition, and fiber length. Depending upon the vacuum in the apparatus, the entire drainage experiment takes only a few seconds so that the drainage velocities are similar to those present on high speed commercial paper machines.

Since drainage experiments are conducted under constant area (A) the drainage velocity (v) is related to the change in the volume (V) in the apparatus as a function of time (t).

$$v = \frac{1}{A}\frac{dV}{dt} \tag{2}$$

The pressure drop across the mat (ΔP_m) is related to the total pressure drop (ΔP_t) and the pressure drop across the forming fabric (ΔP_w).



1. Schematic of new drainage apparatus.

$$\Delta P_m = \Delta P_t - \Delta P_w \tag{3}$$

The total pressure drop (ΔP_t) is measured as a function of time using a pressure transducer shown in Fig. 1. The pressure drop across the forming fabric (ΔP_w) is estimated as a function of drainage velocity from data obtained from a separate experiment in a flow loop.

The mat thickness (L) is estimated from the drainage volume (V), the retention coefficient (R), the drainage area (A) and the properties of the stock:

$$L(t) = \frac{(C_o \, \rho_s) \, R V(t)}{A(1 - \varepsilon_m) \, \rho_p} \tag{4}$$

where C_o and ρ_s are the original consistency and density of the sample entered into the test apparatus. To estimate the mat thickness, values are required for the void fraction (ε_m) and density (ρ_p) of the particles comprising the mat or wet web. Lastly, the drainage resistance (a) can be estimated from the appropriate measurements as a function of time by rearranging equation (1) and by appropriate substitution.

$$a(t) = \frac{\Delta P_t - \Delta P_w}{L \cdot v} = \frac{\Delta P_t(t) - \Delta P_w(t)}{\left[\dfrac{R\rho_s \, C_o}{A^2 \, (1 - \varepsilon_m) \rho_p}\right] V(t) \dfrac{dV(t)}{dt}} \tag{5}$$

Headbox sample # grade	(1) Bond	(2) Highly filled opaque book grade	(3) LWC basesheets
Furnish components	85% HW 15% SW PCC	50% Sulfide 20% SWK 30% HWK 40% added broke 160ppt PCC 100ppt TiO_2	37% SWK 24%TMP 36% GW 3% BCTMP 15% added ctd. broke
Headbox consistency, %	0.43	0.39	0.47
Headbox fines content, %	32.3	36.0	44.0
Headbox ash content, %	20.6	24.4	8.30
Freeness, *csf*	355	103	40

I. Characteristics of headbox samples.

COMPONENT	CANADIAN STANDARD FREENESS (mL)
Stone groundwood	39
TMP	64
Coated broke	112
BCTMP	120
Refined bleached SW kraft	649
Headbox	40

II. Freeness values for components in lightweight coated (LWC) paper.

As the mat thickness increases with time, the resistance increases to reduce the drainage rate. For materials such as solid particles of uniform size, the drainage resistance is constant and is not a function of time. However for pulp suspensions, the resistance coefficient often increases with basis weight. The volume drained converts to basis weight (BW) as:

$$BW(t) = \frac{(C_o \rho_s) R V(t)}{A} \tag{6}$$

We estimated the pressure drop across the forming fabrics in an external flow loop using water shown in Fig. 2. The flow loop consists of a reservoir for holding 20 gal of water, a submersible pump, 1 in. plastic pipe, a rotometer for estimating the flow rate, fabric holder, two manometers open to the atmosphere, and associated valves and fittings. In operation, a sample of the forming fabric is contained within a fabric holder and water is pumped from the 20 gal tank through the flow meter and then through the forming fabric. The pressure drop across the fabric (ΔP_w) is measured with the two manometers located upstream and down stream of the fabric while the superficial fluid velocity is estimated from the reading taken using the flowmeter and the dimensions of the 1-in. pipe.

The data are plotted as pressure drop across the forming fabric (ΔP_w) versus velocity (v). These data are subsequently used to correct the total pressure drop (ΔP_t) according to Eq. (3) for each value of the estimated drainage velocity measured in the drainage apparatus.

For cone and plate type rheometers with small cone angles, the shear rate applied to the fluid can be calculated by the following equation:

$$\gamma = \frac{2\pi\omega}{\tan\alpha} \tag{7}$$

where w is the rotational speed and α is the cone angle.

Experimental conditions

The drainage resistance (α) was determined for a variety of samples. We expect furnishes that have high values of the drainage coefficient (α) and high water retention value (WRV) would also be expected to be difficult to dewater in the press and dryer section of the paper machine.

We tested headbox samples for three different paper grades: bond paper, highly-filled opaque book paper, and base stock used to produce lightweight coated (LWC) publication paper. We chose these grades because they have a wide range of pulps and fines content (**Table I**). The headbox sample for the LWC paper and the highly filled opaque grade came from two local paper mills. The sample for bond paper was taken from the headbox of the experimental fourdrinier paper machine at the University of Maine during papermaking experiments. Table I summarizes the characteristics of the three headbox samples slurries. Filler content determined using a 550°C combustion test ranged from a low of 8.3% for the LWC to 24.4% for the highly filled opaque book grade. Similarly, the total fines content ranged from 32% for the bond paper to 44% for the LWC paper.

We also used the apparatus to determine the drainage resistance for the various pulp components that go to the blend chest in the production of LWC publication paper (**Table II**). In this example, the constituents in the LWC basestock were stone groundwood, thermomechanical pulp (TMP), refined softwood kraft pulp, bleached chemi-thermomechanical pulp (BCTMP), and coated broke. Table II gives the freeness values for the component pulps used in the production of the LWC publication paper. CSF values ranged from 39 mL for the stone groundwood pulp to 649 mL for the refined bleached softwood kraft pulp. Determining the drainage resistance of the component pulps allowed us to compare the drainage resistance of the headbox sample which had a CSF value of about 40 mL.

The cone used in the drainage experiments had an angle of 10° and ran at speeds of 0, 250, 500, 750, and 1000 rpm. This corresponded to shear rates of about 0-594 s^{-1} and shear stresses of 0-0.594 Pa assuming the stock had a viscosity of water. The experiments to characterize the headbox and LWC pulps were only conducted at 500 rpm. The drainage area in the device was approximately 0.0127 m^2 and corresponding to an inside diameter of 12.7 cm. During the experiments, the vacuum setting in the reservoir was set at 15 kPa.

The flow resistance was estimated in the flow loop for a variety of forming fabrics. We selected a triple layer publication grade forming fabric and used it in the drainage experiments to estimate the flow resistance for the headbox and pulp samples. The publication grade forming fabric was 180x165 mesh in the machine- and cross-machine directions respectively. The forming fabric had a void fraction (ε_w) of 48.6% and an equivalent wire diameter (D_p) of 0.255 mm.

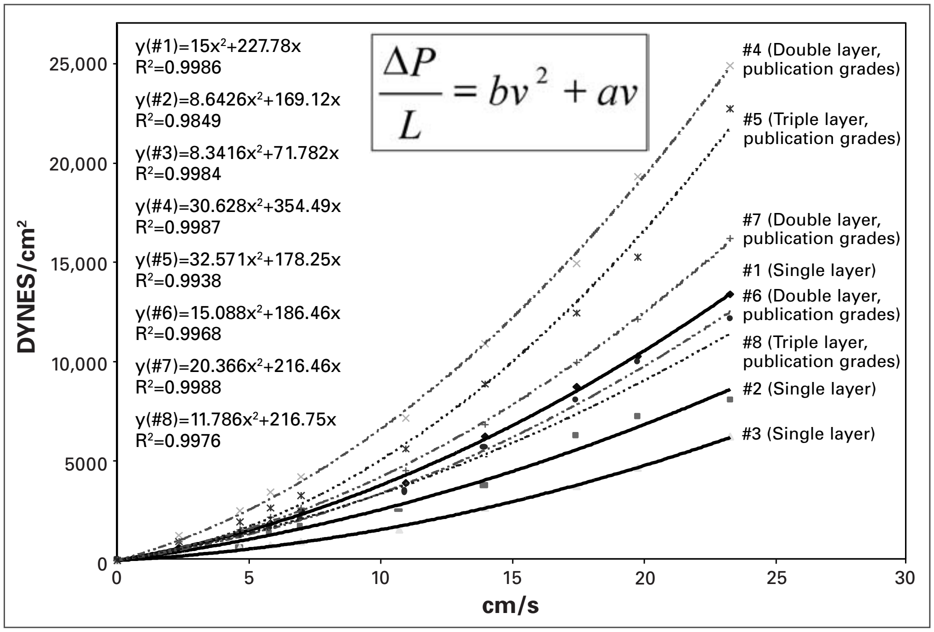
The particle density (ρ_p) and the void fraction in the mat (ε_m) were estimated as described in Paradis *et al* [12]. the particle densities ranged from 1200 to 1450 kg/m^3 depending on the filler content. Values for particle density and viod fraction in the mat are required in Eqs. (3) and (5) to estimate the mat thickness and the drainage resistance.

RESULTS

Forming fabrics flow resistance

Figure 2 shows the results of the pressure drop measurements for a variety of forming fabrics. All of the pressure drop relationships shown in the figure follow a quadratic equation, indicating that the inertial terms become important at high drainage rates. Forming fabrics with low values for the void fraction (ε_w) exhibited the greatest flow resistance. These relationships were used later to estimate the pressure drop of the forming fabric at a given superficial drainage rate.

For flow in porous media over a range of flow rates, the Ergun equation worked well (Bird *et al*. [13]



2. Pressure drop across forming fabrics.

$$\left(\frac{\Delta P_w \rho}{G_o^2}\right)\left(\frac{D_p}{L_w}\right)\left(\frac{\varepsilon_w^3}{1-\varepsilon_w}\right) = 150\left(\frac{1-\varepsilon_w}{(D_p G_o/\mu)}\right) + 1.75 \tag{8}$$

In the Ergun relationship, ΔP_w is the pressure drop, ρ is the fluid density, D_p is the mean diameter of the wires comprising the fabric, ε_w is the void fraction of the fabric, L_w is the thickness of the wire, G_o is the mass flow velocity, and μ is the fluid viscosity. We calculated the mean diameter (D_p) from the surface area per unit volume (A_v) for the forming fabrics using the following equation.

$$D_p = \frac{6}{a_v} \tag{9}$$

We approximated the parameter (a_v) from the surface area and volume of the forming wires comprising the fabric. We did this by estimating the dimensions of the forming wires and by counting the strands under a microscope.

When the experimental data were plotted in the form of the Ergun equation, a line is obtained with a slope of 167 and an intercept of 1.78, which are close to the coefficients of 150 and 1.75 in Eq. (8). **Figure 3** shows the results. The correlation coefficient (R^2) for the Ergun equation was 0.871, which indicates a reasonable fit of the data. Considering the accuracy of measuring the above parameters, this result is excellent. This result is a good validation of the Ergun equation and is a powerful method to predict the resistance of a given fabric from the basic properties of the wire diameter, thickness, and void fraction.

Drainage cell

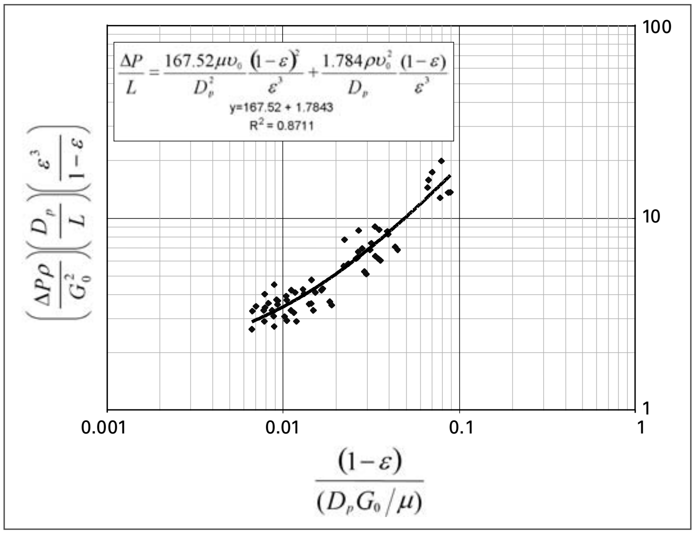
Figures 4 shows typical output results from the drainage apparatus. At about 1 s on the time axis, the valve is opened, and the pressure transducer sees a pressure drop across the wire and any mat that has formed. The pressure beneath the forming fabric reaches the steady state value within about 0.2 s. The volume remaining in the shear cell decreases at a rapid rate. The rate of drainage decreases as a mat forms on the wire. The important experimental data are collected within about 2 s. **Figure 5** illustrates how the pressure changes beneath the wire as the drainage velocity changes. The velocity is calculated by taking the difference in volume in the cell and dividing by the change in time and the drainage area. The drainage velocity at zero time is estimated from the pressure drop at that time and the wire resistance.

We ran six replicate drainage runs for each experimental condition and averaged the separate curves to obtain an average result. The increase in drainage velocity at short times is a result of the time required to accelerate the fluid mass. As the mat builds up on the wire, the drainage velocity decreases. The coefficient of variation, or the percent difference between the individual runs and the mean, is 15% to 20%. We estimated the potential initial velocity, with no mat, from the data in Fig. 2 by knowing the pressure drop imposed. The start-up transient does not invalidate the latter time data.

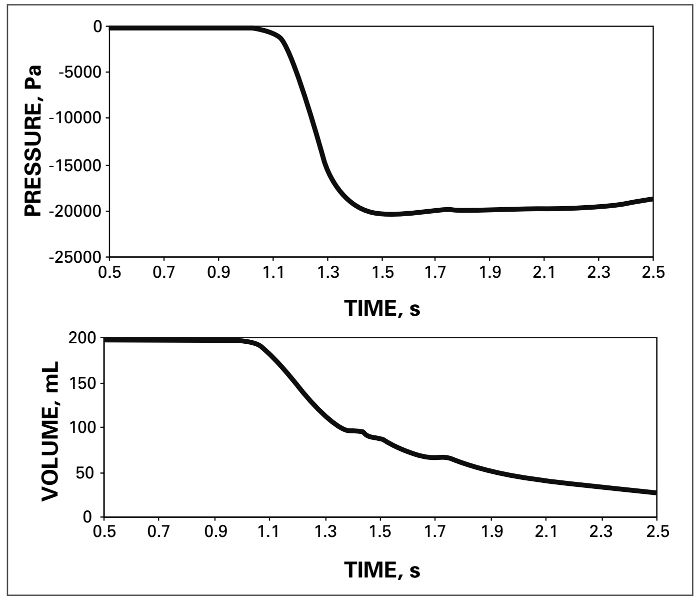
Shear rate and the drainage resistance coefficient

Figure 6 shows the effect of shear rate on the drainage resistance coefficient (a) and ash retention. The figure plots the drainage resistance as a function of stirrer rpm for different basis weights of the mat that was formed (dry weight basis). We calculated the shear rates from Eq. (7). They linearly depend on rpm in which 0 to 1000 rpm relates to 0 and 594 s^{-1}. The stirring speed corresponded to a shear stress (t) of 0 to 0.6 Pa, assuming that the slurry behaved as a Newtonian fluid and had a viscosity equal to that of water. We estimate that 85% of the wire area sees this shear rate. As expected, the retention decreases with increasing shear rate.

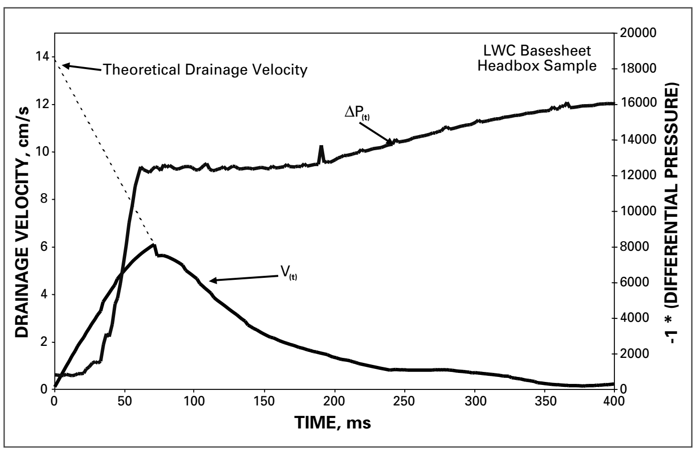
Figure 6 shows that there is an increase in drainage resistance with an increase in shear rate up to a maximum of about 700 to 800 rpm. The maximum depended upon the weight of the fiber mat formed. At low mat weights (and thickness) there



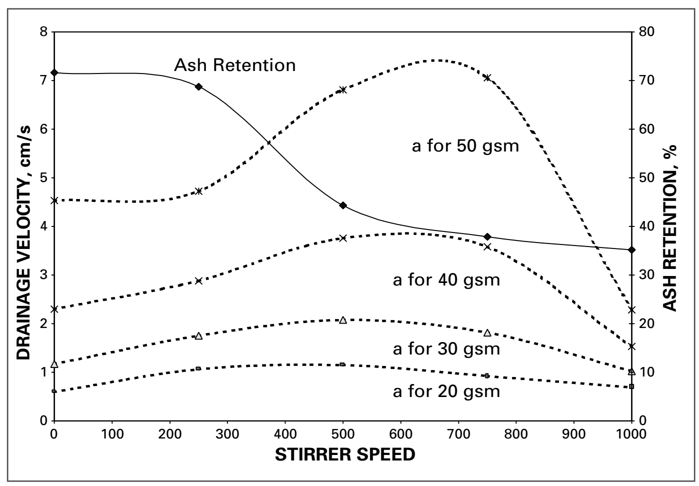
3. *Correlation of pressure drop across commercial forming fabric.*



4. *Sample output from drainage device.*



5. *Pressure and velocity at short times. Drainage rate at zero time is estimated from wire resistance and the applied pressure.*



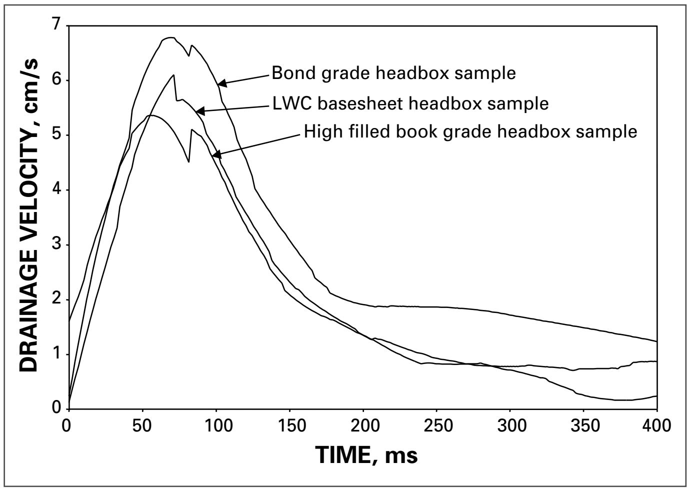
6. *Effects of shear rate on drainage resistance and retention.*

was little increase in the resistance. As the basis weight increases, the increase in resistance is more pronounced. Even at high mat thicknesses, the resistance coefficient drops sharply above a stirrer speed of 800 rpm. The initial increase in drainage resistance with increasing shear rate may be a result of the increasing force from the stirrer compressing the mat. The increase in resistance may be a result of the shear field that helps the fibers to deposit into a tighter packing. The decrease in drainage resistance at the higher shear rates may be due to the disruption or removal of the mat from the forming fabric. In some cases, this disruption was evident at the end of the experiments. The shear rate or stress to disrupt the mat may be an important characteristic of the wire and the pulp that can now be characterized by these experiments. This mat disruption may be a function of the fiber type, retention system, filler content, and wire type.

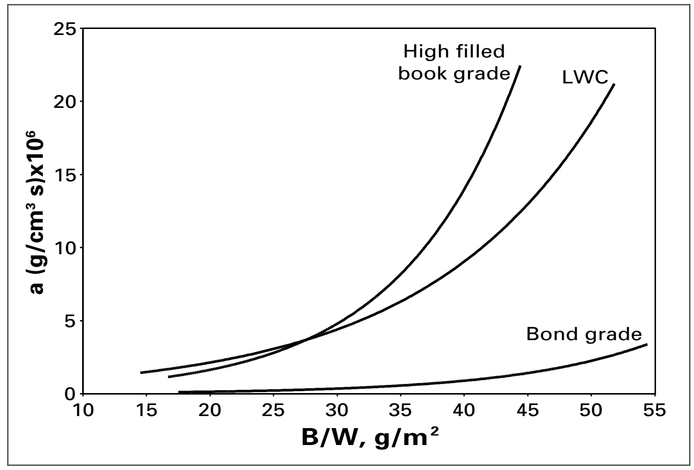
We used a value of 500 rpm for the remainder of the experiments presented below. A rotational speed of 500 rpm gives rise to a shear rate of about 298 s^{-1} and corresponds to a shear stress of 0.3 Pa. Franzen [14] presents a numerical design model for predicting drainage on twin wire and top wire units. Franzen's model permits estimation of the shear rate and stresses present as the wet web passes over forming blades in top wire units. Numerical calculations performed for a newsprint furnish using the Franzen model suggest that using a rotational speed of 500 rpm approximates the shear stress on a commercial top wire unit. Additionally, this stirring speed proved to be convenient to use experimentally.

Headbox samples

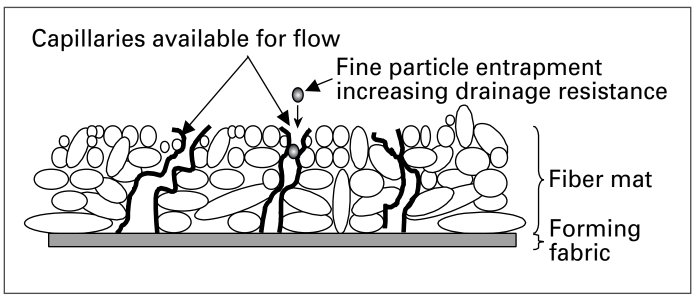
The drainage velocities for the three headbox samples investigated are summarized in **Fig. 7** at a stirring speed of 500 rpm.



7. Drainage velocity vs. time curves for headbox samples.



8. Average drainage resistance coefficients for grades listed in Table I.

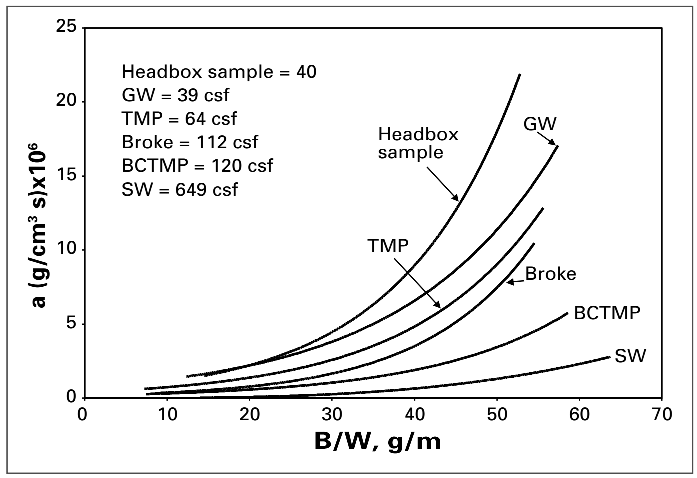


9. Schematic of the effect of fine particle plugging.

There are small differences in consistency between the three samples, but they vary only between 0.4% to 0.5%. All three of the headbox samples show the same increase in the velocity at short times because the same forces are required to accelerate the fluid. However, at around 60 ms, significant differences are apparent. The bond grade headbox sample shows a higher drainage rate for the entire time when compared to the samples for the highly filled opaque book grade or the LWC basestock. This indicates that the mat formed is more open. Even at 200 ms, the bond grade sample has a higher drainage velocity, even though the mat formed at this point should be thicker than the mat with the LWC sample or the book grade pulp.

Figure 8 illustrates the results after we converted the velocity data into a resistance coefficient. The headbox sample for the bond grade had a freeness of 355 mL compared to the 40 mL for the LWC basesheet and the 103 mL for the sample for the highly filled opaque grade. Figure 8 shows that the bond grade stock had a much lower, and mostly constant drainage resistance coefficient compared to the LWC and book grade.

If the mat formed on the wire had constant physical properties, the drainage resistance would be constant. The increase in the drainage coefficients for all three samples shows that the characteristics of the mats change as drainage occurs. This is thought to be due to the fine material plugging the drainage channels as the mat is formed [9]. The viscous resistance coefficient (a) should be proportional to the porosity of the mat



10. Drainage resistance coefficients for furnish components for LWC base sheet.

(ε_m), the surface area per unit volume (S_v) of the particles trapped in the mat, and the viscosity (μ) as in the Carman-Kozeny relationship as

$$a = \frac{k_1 (1-\varepsilon_m)^2}{\varepsilon^3} S_v^2 \mu \qquad (10)$$

Figure 9 illustrates this schematically. The bond grade sample shows only a slight increase, but the other samples indicate an increase by a factor of five. The bond grade sample has a low level of fine material.

Figure 10 shows the results for the constituent pulp samples comprising the furnish going to the blend chest for the LWC sample. Table II gives the constituents and the freeness values for the pulps. The headbox sample shows the largest increase in the resistance coefficient while the softwood sample the lowest. The order for the components in the furnish with decreasing drainage resistance is the stone groundwood, followed by the TMP, broke, BCTMP and finally the refined softwood kraft pulp, although the latter was refined very little. The headbox sample had a higher drainage resistance coefficient than any of the component pulps. We believe this resulted from the introduction of fine particles contained in the white water used to dilute the component pulps to the headbox consistency. The important point is that the drainage properties of these various pulps can be characterized by the drainage resistance test and inserted into the available computational models. The new aspect reported here is that the shear rate and shear stress for these drainage conditions are known. Figure 10 also serves as the start of a database that can be developed for various pulps and can be used for designing formers.

CONCLUSIONS

The flow resistance data for the forming fabric agree with the Ergun equation. Therefore, if the equivalent diameter, thickness, and the void fraction of the fabric are known, the flow resistance of the wire can be predicted. This relationship may be of use in designing fabric for papermaking applications.

The modified drainage apparatus described here permits drainage resistance coefficients to be determined under a known shear condition at high drainage rates and at short times. At low shear rates, the drainage resistance increases with increasing shear rate. At higher shear rates, the resistance decreases with increasing shear rate. This decrease may be a result of the mat being removed by shear forces from the wire.

The drainage resistance coefficients for both the pulp and headbox samples are a function of the basis weight under shear conditions. The increase in drainage resistance coefficient with basis weight may be related to pore plugging which alters the effective void fraction of the forming mat. **TJ**

LITERATURE CITED

1. Zhao, R.H., and Kerekes, R.J., *J. Pulp Paper Sci.* 21(3): 97(1995).
2. Zahrai, S., and Bark, F.H., *Nordic Pulp Paper Res. J.*, 10(4): 245(1995).
3. Roshanzamir A., Green, S.I. , and Kerekes, R.J., *J. Pulp Paper Sci.* 24(11): 364(1998).
4. Green, S.I., *J. Pulp Paper Sci.* 23(7): 353(1997).
5. Green, S.I., Zhao, R.H., and Kerkes, R.J., *J. Pulp Paper Sci.*, 24(2): 60(1998).
6. Dalpke, B., Green, S., and Kerkes, R.J., "Modelling of jet impingement in twin-wire paper machines: impingement on one fabric," *TAPPI J.*, 84(2):44 (2001); published online at www.tappi.org.
7. Mantar, E., Co, A., and Genco, J.M., *J. Pulp Paper Sci.* 21(2): 44(1995).
8. Wildfong, V.J., Genco, J.M., Shands, J.A., and Bousfield, D.W., *J. Pulp Paper Sci.* 26(7): 250(2000).
9. Wildfong, V.J., Genco, J.M., Shands, J.A., and Bousfield, D.W., *J. Pulp Paper Sci.* 26(8): 280(2000).
10. Hung, L., Leung, W. K., and Green, S. I., "Pulp fiber mat permeability measurement under simulated forming conditions," 2000 TAPPI Engineering Conference Proceedings, TAPPI Press, Atlanta, Georgia, USA (2000).
11. Arslan, K., Bousfield, D.W., and Genco, J.M., *TAPPI J.* 80(1): 254(1997).
12. Paradis, M.A., Genco, J.M., Hassler, J.C., and Wildfong, V.J., "Determination of drainage resistance coefficients under conditions of known sheer rate", 2001 TAPPI Engineering Conference.
13. Bird, R.B., Stewart, W.E., and Lightfoot, E.N., Transport Phenomena, p. 200, Wiley Press, New York., New York, USA (1960).
14. Franzen, M. F., "Simulation and optimization of the papermaking sheet forming process," *Proceedings of the 2000 ASME Fluids Engineering Division Summer Meeting*, ASME International, New York, New York, USA.

Received: July 19, 2001
Accepted: December 20, 2001

This paper was originally presented at the 2001 TAPPI Engineering Conference.

This paper is also published on TAPPI's web site (www.tappi.org) and summarized in the August Solutions! for People, Processes and Paper magazine (Vol. 85 No. 8).

Paradis, Genco, Bousfield, and Hassler are with the Department of Chemical Engineering, University of Maine, Orono, Maine, USA; Wildfong is with Johnson Foils Corp., Springfield, Massachusetts, USA. Email Paradis at mparadis@maine.edu.


Paradis


Genco


Bousfield


Hassler


Wildfong